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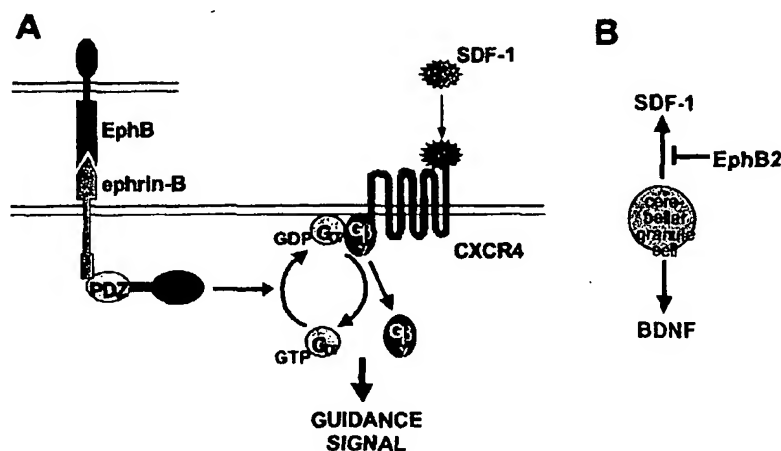
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(54) Title: B-EPHRIN REGULATION OF G-PROTEIN COUPLED CHEMOATTRACTION; COMPOSITIONS AND METHODS OF USE



(57) Abstract: Transmembrane B ephrins and their Eph receptors signal bi-directionally. The presently claimed invention describes a cytoplasmic protein, designated PDZ-RGS3, which binds B ephrins through a PDZ domain, and has a regulator of heterotrimeric G protein signaling (RGS) domain. PDZ-RGS3 mediates signaling from the ephrin-B cytoplasmic tail. SDF-1, a chemokine with a G protein coupled receptor, or BDNF, act as chemoattractants for cerebellar granule cells, with SDF-1 action being selectively inhibited by soluble EphB receptor. The claimed invention reveals a pathway that links reverse signaling to cellular guidance, uncovers a novel mode of control for G proteins, and demonstrates a mechanism for selective regulation of responsiveness to neuronal guidance cues. Further, compositions and methods of use are provided for modulating cell migration as a function of chemokines and GPCR interaction, to aid in the treatment of disease states and medical conditions, including cancer and immune responses such as allergy and autoimmune responses. In one embodiment, a method of altering the sensitivity of a cell to a chemokine is provided using a PDZ-RGS3 protein.



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**B-Ephrin Regulation of G-Protein Coupled Chemoattraction; Compositions  
and Methods of Use**

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**Technical Field and Background Art**

The present invention relates to ephrin reverse signaling in vertebrate cells, particularly cerebellar granular cells and leukocytes, the signaling acting through a novel PDZ-RGS protein, to block a heterotrimeric G protein pathway. This signaling results in inhibition of the chemoattractant effects of a chemokine, in particular, of SDF-1. Methods and compositions for modulation of the pathway provide potential therapeutic agents for inflammation and autoimmune diseases.

Chemoattractant cytokines or chemokines are a family of proinflammatory mediators that promote recruitment and activation of multiple lineages of leukocytes and lymphocytes. They can be released by many kinds of tissue cells after activation.

Continuous release of chemokines at sites of inflammation mediates the ongoing migration of effector cells in chronic inflammation. The chemokines characterized to date are related in primary structure. They share four conserved cysteines, which form disulfide bonds. Based upon this conserved cysteine motif, the family is divided into two main branches, designated as the C-X-C chemokines ( $\alpha$ -chemokines), and the C-C chemokines ( $\beta$ -chemokines), in which the first two conserved cysteines are separated by an intervening residue, or adjacent respectively (Baggiolini, M. and Dahinden, C. A., Immunology Today, 15:127-133 (1994)).

The C-X-C chemokines include a number of potent chemoattractants and activators of neutrophils, such as interleukin 8 (IL-8), PF4 and neutrophil-activating peptide-2 (NAP-2). The C-C chemokines include RANTES (Regulated on Activation, Normal T Expressed and Secreted), the macrophage inflammatory proteins 1 $\alpha$  and 1 $\beta$

(MIP-1 $\alpha$  and MIP-1 $\beta$ ), and human monocyte chemotactic proteins 1-3 (MCP-1, MCP-2, MCP-3), which have been characterized as chemoattractants and activators of monocytes or lymphocytes but do not appear to be chemoattractants for neutrophils. Chemokines, such as RANTES and MIP-1 $\alpha$ , have been implicated in a wide range of human acute and chronic inflammatory diseases including respiratory diseases such as asthma and allergic disorders.

The chemokine receptors are members of a superfamily of G protein-coupled receptors (GPCR) which share structural features that reflect a common mechanism of action of signal transduction (Gerard, C. and Gerard, N. P., *Annu Rev. Immunol.*, 12:775-808 (1994); Gerard, C. and Gerard, N. P., *Curr. Opin. Immunol.*, 6:140-145 (1994)). Conserved features include seven hydrophobic domains spanning the plasma membrane, which are connected by hydrophilic extracellular and intracellular loops. The majority of the primary sequence homology occurs in the hydrophobic transmembrane regions with the hydrophilic regions being more diverse.

The superfamily of GPCRs has at least 250 members (Strader et al. *FASEB J.*, 9:745-754, 1995; Strader et al. *Annu. Rev. Biochem.*, 63:101-32, 1994). It has been estimated that one percent of human genes may encode GPCRs. GPCRs bind to a wide-variety of ligands ranging from photons, small biogenic amines (i.e., epinephrine and histamine), peptides (i.e., IL-8), to large glycoprotein hormones (i.e., parathyroid hormone). Upon ligand binding, GPCRs regulate intracellular signaling pathways by activating guanine nucleotide-binding proteins (G proteins). GPCRs play important roles in diverse cellular processes including cell proliferation and differentiation, leukocyte migration in response to inflammation, and cellular response to light, odorants, neurotransmitters and hormones (Strader et al., *supra.*).

Over the last fifteen years it has become apparent that many ligands that signal through cell surface receptors are themselves transmembrane molecules (Pfeffer and Ullrich, 1985; Flanagan et al., 1991; Massague and Pandiella, 1993). One function of this ligand anchorage may be to tightly localize the signal. This idea is particularly well exemplified by the ephrins, since they require membrane anchorage to activate their receptors in a direct cell-cell contact mechanism, and since they have spatially precise patterning roles.

A second potential function for transmembrane ligands is to allow bi-directional signaling. Again, the ephrins have provided a particularly good model system to investigate this idea. Reverse signaling through B ephrins has been demonstrated biochemically by ligand phosphorylation. Evidence of important developmental roles has come from genetic and embryological studies of whole embryos or tissues.

Ligands in the ephrin-B family are cell surface anchored by a transmembrane domain, and signal through their Eph receptors by direct cell-cell contact (Davis et al., 1994; Drescher et al., 1997; Flanagan and Vanderhaeghen, 1998; Frisen et al., 1999; Holder and Klein, 1999; Mellitzer et al., 1999). This contact-mediated mechanism provides the potential for bi-directional signaling, with a forward signal through the tyrosine kinase receptor, and a reverse signal through the ligand. Reverse signaling has been demonstrated biochemically by studies showing B ephrins become phosphorylated upon treatment of cells with soluble EphB-Fc receptor fusion protein (Holland et al., 1996; Bruckner et al., 1997). In the context of whole organisms or tissues, genetic and embryological studies have supported important roles for B ephrin reverse signaling in developmental processes, including axon pathway selection, blood vessel formation, and rhombomere compartmentation (Henkemeyer et al., 1996; Jones et al., 1998; Wang et al., 1998; Adams et al., 1999; Gerety et al., 1999; Mellitzer et al., 1999; Xu et al., 1999).

However, little is known of the specific effects of B ephrin reverse signaling on individual cells, or the signal transduction pathways that lead to such effects.

Evidence that B ephrins might interact with cytoplasmic proteins initially came from sequence comparison of ephrin-B1 and -B2, which show a striking 100% amino acid identity in the last 33 amino acids of the intracellular domain (Bennett et al., 1995; Bergemann et al., 1995). Using the intracellular domain in yeast two-hybrid screens, several binding proteins have been identified (Torres et al., 1998; Bruckner et al., 1999; Lin et al., 1999). All the binding proteins identified to date contain a PDZ (PSD-95/Dlg/ZO-1) domain, a protein module that binds the C-termini of membrane proteins. PDZ proteins have been widely implicated in forming sub-membrane scaffolds that cluster molecules at the cell surface (Craven and Bredt, 1998; Garner et al., 2000; Sheng and Pak, 2000).

RGS proteins form a large molecular family identified in recent years, with more than 20 members in mammals (Arshavsky and Pugh, 1998; Kehrl, 1998; De Vries and Farquhar, 1999; Zheng et al., 1999). They act as GTPase activating proteins (GAPs) for heterotrimeric G proteins, accelerating the G protein catalytic cycle and thereby facilitating rapid signaling processes such as retinal phototransduction (Arshavsky and Pugh, 1998). Many RGS proteins contain additional motifs, including PDZ domains, leading to suggestions that they could couple G proteins with other signaling pathways (Kehrl, 1998; De Vries and Farquhar, 1999). The RGS protein p15RhoGEF has separate domains that regulate both heterotrimeric and small G proteins, while nematode EAT-16 mediates a genetic interaction between two heterotrimeric G protein pathways (Hart et al., 1998; Kozasa et al., 1998; Hajdu-Cronin et al., 1999). However, there is generally little functional evidence on the specific significance of combining RGS domains with

other domains, including a potential role for PDZ-RGS proteins in regulating G proteins in response to extracellular signals.

Heterotrimeric G protein-coupled receptors (GPCRs) are seven-transmembrane proteins that mediate the effects of many extracellular signals (Watson and Arkinstall, 1994; Bargmann and Kaplan, 1998). Some of the best characterized guidance molecules act through GPCRs (Parent and Devreotes, 1999), notably the chemokines, which are leukocyte chemoattractants with important roles in immunity (Melchers et al., 1999). A role for chemokines in neural development was shown more recently. The radial movement of cerebellar granule cells is a well characterized model for neural migration (Rakic, 1990; Hatten, 1999) and occurs prematurely in mice with gene disruptions of the chemokine SDF-1, or its receptor CXCR4 (Ma et al., 1998; Zou et al., 1998).

Heterotrimeric G protein signaling may also mediate, at least in part, the actions of Netrins, Semaphorins and other neural guidance molecules, though these pathways are generally less well understood (Vancura and Jay, 1998; Corset et al., 2000; Nakamura et al., 2000).

### **Summary of the Invention**

In one aspect, an embodiment of the invention provides an amino acid sequence having a PDZ domain and an RGS domain. An embodiment of the invention is a protein comprising an amino acid sequence substantially identical to that shown in SEQ ID NO: 1. Further, an embodiment of the invention is a nucleic acid encoding the amino acid sequence of the protein. The nucleic acid is an isolated nucleotide sequence encoding the amino acid sequence of the protein. Further, a nucleic acid that hybridizes to this nucleic acid is provided, as is a recombinant vector, and a recombinant cell containing the vector,

comprising any of these nucleic acids. In one embodiment, the protein is encoded by a gene from a vertebrate, for example, the vertebrate is a mammal.

In a further aspect, an embodiment of the invention is a protein encoded by a gene, the protein having an RGS domain and a PDZ domain, the PDZ domain being  
5 capable of binding to a portion of a cytoplasmic domain of an ephrin-B2 in a cell. For example, the binding occurs in a two-hybrid system in a yeast cell, wherein the ephrin-B2 cytoplasmic domain is used as the bait of the system. Further, the mammalian cDNA library is obtained from a tissue selected from the group consisting of an embryo, a tumor or a leukemia, for example, the tumor is of neural origin, for example, the tumor of neural  
10 origin is a neuroblastoma.

In a further aspect, an embodiment of the invention is a protein having an RGS domain and a PDZ domain or a protein comprising an amino acid sequence substantially identical to that shown in SEQ ID NO: 1, wherein the protein causes stimulation of ephrin-B1 induced de-adhesion of embryonic test cells at levels of ephrin-B1 that are  
15 suboptimal, for example, when the stimulation is at least 2-fold, for example at least 4-fold, or at least 8-fold. Further, the stimulation is dependent on the presence of an amino acid sequence present in the carboxy terminal RGS domain, or the stimulation is reversed in a dose-dependent manner in the presence of the amino terminal PDZ domain and in the absence of the carboxy terminal RGS domain. Further, the embryonic test cells are from  
20 an embryo of a cold-blooded vertebrate, for example, the vertebrate is an amphibian.

In a further aspect, an embodiment of the invention is a soluble eph2 receptor capable of binding a cell, such that a pattern of migration of the cell is altered.

In a further aspect, an embodiment of the invention is a method of altering sensitivity of a cell to a chemokine, comprising: transmitting a reverse signal from a  
25 recombinant soluble ephB2 receptor to a transmembrane protein in the cell which is a



ligand of the ephB2 receptor; binding a cytoplasmic protein, the cytoplasmic protein having an RGS domain and a PDZ domain, to the cytoplasmic domain of the transmembrane protein in the cell; and altering a reaction of a G-protein coupled receptor (GPCR) in the membrane of the cell, such that the cell has altered sensitivity to a chemoattractant chemokine. Further, the cell is selected from the group of: a leukocyte; a granule cell located in an external granule cell layer (EGL) of a developing brain cerebellum; a cell involved in migration, blood vessel formation, axon pathway selection, or rhombomere compartmentation. The transmembrane protein is substantially homologous to an ephrin-B2, or transmission of the reverse signal requires a presence of the PDZ-RGS3 protein in the first cell, or the chemokine is an SDF-1, for example, transmission of the reverse signal causes loss of responsiveness of the cell to the SDF-1. Further, when the cell is a leukocyte, the method by which the cell loses sensitivity to the chemokine is a treatment for an inflammatory condition or an autoimmune disease. Further, an embodiment of the invention provides omitting the recombinant soluble ephB2 and screening the sample for a chemical agent that substitutes functionally for the omitted ephB2, the method comprising adding a test sample to screen the sample for the presence of the agent that alters sensitivity of the cell to the chemokine.

In a further aspect, an embodiment of the invention is a method of modulating an intracellular pathway involved in cell migration upon the event of a cell to cell contact, comprising: initiating ephrin signaling by providing cell to cell contact in a cell having a cytoplasmic protein, the cytoplasmic protein having an amino terminus that interacts with the carboxy terminus of ephrin, and having a carboxy terminus that affects a GTP-linked reaction of a seven transmembrane protein, causing the cell in the presence of sufficient chemokine to otherwise inhibit such migration from an initial anatomical location and towards a target location. Further, the method involves selecting the cell from a group

consisting of a granule cell and a leukocyte, such that the protein mediates an intracellular pathway that causes the granule cell to migrate away from the EGL, or that causes the leukocyte to migrate into an inflamed tissue, respectively.

In a further aspect, an embodiment of the invention is a method of screening for  
5 the presence in a test sample of an agent that alters in vivo functional interactions among  
the components of an ephrin-B signal pathway involving chemoattraction by a  
chemokine, comprising: placing chemokine-sensitive cells having the ephrin-B ligand on  
a top side of a filter in an upper chamber of a transwell system, wherein the filter has  
pores of uniform size and separates the upper chamber from a lower chamber, and  
10 wherein the lower chamber contains the chemokine; adding a test sample to the lower  
chamber; and analyzing the lower side of the filter to determine an amount of migration  
of the cells into the lower chamber. Further, the method comprises having a second  
transwell such that adding a test sample to the lower chamber of the second transwell is  
omitted as a control, and further comparing the amount of migration of cells in the  
15 presence and absence of the test sample is an indication of the effect of the agent on cell  
migration. Further, the cells are selected from a purified preparation of cerebellar granule  
cells and a pure cultured leukocyte cell line; further, the chemokine can be SDF-1.  
Further, the lower chamber contains the chemokine at a sub-optimal level, wherein the  
agent in the test sample causes a decrease in cell migration in comparison to the second  
20 transwell control. The agent is an anti-inflammatory or an anti-autoimmune therapeutic  
composition. Further, the agent causes a increase in cell migration in comparison to the  
control, for example, the agent is a novel chemokine, or the agent is a low molecular  
weight synthetic organic chemical.

In other embodiments according to the claimed invention, a pharmaceutical  
25 composition is described for delivering to a selected site an effective dose of a protein

having an RGS domain and a PDZ domain capable of altering the sensitivity of a cell to a chemokine comprising an effective dose of said protein and a suitable carrier, and optionally additional active or inert ingredients such as diluents, stabilizers, and excipients.

5        Another embodiment in accordance with the present invention includes a pharmaceutical composition for delivering to a selected site an effective dose of a protein having an RGS domain and a PDZ domain capable of altering the sensitivity of a cell to a chemokine comprising an effective dose of said protein and a suitable carrier, and optionally additional active or inert ingredients such as diluents, stabilizers, and  
10        excipients, wherein the pharmaceutical composition is administered intradermally, intramuscularly, subcutaneously, topically, or in the form of a vector. In addition, the presently claimed invention describes a pharmaceutical composition as above further comprising a substance that allows for the slow release of the pharmaceutical composition at the selected site. Still yet another embodiment in accordance with the  
15        present invention is a pharmaceutical composition as above wherein the selected site for delivery is a tumor site, or an allergic response site, or an autoimmune response site.

Another embodiment in accordance with the present invention is a viral vector comprising the nucleic acid sequence encoding the protein of SEQ ID NO.1. And another embodiment in accordance with the present invention is a plasmid comprising the  
20        nucleic acid sequence encoding the protein of SEQ ID NO.1.

### **Brief Description of the Drawings**

The foregoing features of the invention will be more readily understood by reference to the following detailed description, taken with reference to the accompanying drawings, in which:

5        Figure 1 is a general overview of the primary structure of PDZ-RGS3.

      Fig1A shows the domain structure of mouse PDZ-RGS3. Human RGS3 is diagrammed below.

      Fig. 1B is a dendrogram showing sequence homologies among representative human and mouse RGS proteins. For relationships with additional proteins, see Zheng et  
10    al. (1999). The Clustal program was used to align the RGS domains.

      Fig. 1C is the amino acid sequence of mouse PDZ-RGS3 is deduced from the cDNA nucleotide sequence. PDZ and RGS domains are boxed. The human RGS3 sequence is aligned, with identical amino acids indicated by shading.

      Fig. 2 shows the binding interaction between PDZ-RGS3 and B ephrin.

15        Fig. 2A is a GST fusion protein pull-down assay. GST-ephrin-B 1 affinity beads were incubated with 35S-labeled PDZRGS3 or mutant derivatives. Bound proteins were resolved on SDS gel and autoradiographed. GST fusion protein on the affinity beads was Coomassie blue stained to ensure similar amounts (lanes 10 and 11).

      Fig. 2B shows co-immunoprecipitation from transfected cells. HA-tagged  
20    ephrin-B1 and myc-tagged PDZ-RGS3 were co-transfected into COS cells. Cell lysates were immunoprecipitated with anti-HA or anti-myc antibody. After Western blot, each membrane was cut into an upper half with proteins above 80 kDa, probed with anti-myc antibody to detect myc-PDZ-RGS3 or myc-SAP97, and the lower half probed with anti-ephrin-B.

25        Fig. 2C shows co-immunoprecipitation of endogenously expressed PDZ-RGS3 and ephrin-B1. Lysates of CHP100 neuroblastoma cells (lane 1) or mouse cerebral

cortex (lanes 2 and 3) were immunoprecipitated with anti-ephrin-B1 A20 antibody (lanes 1 and 2) or control rabbit immunoglobulin (lane 3). Immunoprecipitates were Western blotted and probed with anti-PDZ-RGS3. PDZ-RGS3 expressed by transfection in 293T cells was used as a marker (lane 4).

5        Fig. 2D shows co-localization of staining in transfected COS cells (examples arrowed). Cells were co-transfected with myc-PDZ-RGS3 and HA-ephrin-B1, then permeabilized and immunostained with anti-ephrin-B and anti-myc.

      Fig. 3 shows co-localized expression of PDZ-RGS3 and B ephrins in mouse embryos. *In situ* hybridization was used to localize RNAs for PDZ-RGS3, ephrin-B1 or  
10    ephrin-B2, at embryonic stages indicated.

      Fig. 3A shows Ephrin-B1 localization in parasagittal sections of the brain in the ventricular zone (VZ) of the cerebral cortex.

      Fig. 3B shows PDZ-RGS3 localization in parasagittal sections of the brain in the ventricular zone (VZ) of the cerebral cortex.

15        Fig. 3C shows Ephrin-B2 localization in parasagittal sections of the brain in the cerebellar primordium (CP).

      Fig. 3D shows PDZ-RGS3 localization in parasagittal sections of the brain in the cerebellar primordium (CP).

      Fig. 3E shows Ephrin-B1 and B2 localization in parasagittal sections of whole  
20    embryo in dorsal root ganglia (DRG).

      Fig. 3F shows PDZ-RGS3 localization in parasagittal sections of whole embryo in the dorsal root ganglia (DRG).

      Fig. 4 shows PDZ-RGS3 mediation of cell dissociation signaling by ephrin-B1 in *Xenopus* embryos. RNAs encoding various ephrin-B1 or PDZ-RGS3 constructs were  
25    injected alone or in combinations into 2-cell embryos. Embryos were scored for

dissociation at stage 8.5; error bars show SEM. RNA amounts are indicated in nanograms, and the constructs are diagrammed below: ephrin-B1 is shown in green with the C-terminal PDZ binding motif as a rectangle; PDZ-RGS3 is shown with the PDZ domain in yellow and the RGS domain in orange.

5        Figure 5 shows expression in postnatal developing cerebellum.

Fig. 5A shows localization of RNAs for ephrin-B2, EphB2, SDF-1 and CXCR4 using *in situ* hybridization in parasagittal sections of mouse brain at the postnatal stages indicated. Migration of cerebellar granule cells inward from the EGL begins around P3. SDF-1 expression is seen in the pial membrane overlying the cerebellum, while its  
10    receptor CXCR4 shows expression in the cerebellar EGL, at P0 and P3. Expression of ephrin-B2 and its receptor EphB2 is low or undetectable at P0 but is seen clearly in the EGL at P3.

Fig. 5B shows immunofluorescence of purified cerebellar granule cells. Cells are stained with EphB2-Fc, or with antibodies to CXCR4, PDZ-RGS3, or ephrin-B (antibody  
15    C18, which recognizes ephrin-B1 or -B2), or control rabbit immunoglobulin. The top two panels show the same cell stained with different fluorochromes.

Fig. 5C shows purified granule cells treated unfixed with EphB2-Fc receptor fusion protein, then fixed, permeabilized and stained with anti-PDZ-RGS3 (red) and anti-Fc (green). Patches on the cell body and cell processes show co-staining (examples  
20    indicated by arrowheads and arrows).

Figure 6 shows regulation of cerebellar granule cell chemotaxis. Granule cells purified from P8 or P9 mouse cerebellum are placed in the upper chamber of a Transwell apparatus, and cells migrating to the lower side of the filter are counted. Error bars show SEM.

Fig. 6A shows chemotaxis of granule cells to SDF-1 placed in the lower chamber. This chemotaxis is inhibited by EphB2-Fc placed in the upper chamber. EphB2-Fc by itself, here placed in the upper chamber, has no detectable effect. Control Fc does not block granule cell chemotaxis to SDF-1.

5 Fig. 6B shows chemotaxis of granule cells to BDNF placed in the lower chamber. EphB2-Fc does not inhibit chemotaxis to BDNF.

Fig. 6C shows the effect of PDZ-RGS3<sup>PDZ-EGFP</sup> on chemotaxis. PDZ-RGS3<sup>PDZ-EGFP</sup>, a dominant negative truncated form of PDZ-RGS3, was fused to an EGFP fluorescent marker and introduced into purified cerebellar granule cells using a Sindbis viral vector. Fluorescently labeled granule cells expressing PDZ-RGS3<sup>PDZ-EGFP</sup> still show chemotaxis to SDF-1, but the inhibitory effect of EphB2-Fc on chemotaxis is now blocked.

10

Figure 7 shows molecular and cellular mechanisms of reverse signaling.

Fig. 7A shows a molecular model for reverse signaling through B ephrins. Binding of B ephrins and their EphB receptors results in bi-directional signaling. Heterotrimeric G protein signaling is activated by ligands that act through seven -transmembrane receptors, such as the chemoattractant SDF-1 and its receptor CXCR4. PDZ-RGS3 binds the cytoplasmic C-terminus of B ephrins through its PDZ domain, and inhibits heterotrimeric G protein signaling through the GAP activity of its RGS domain.

15

20 These interactions provide a link between ephrin reverse signaling and G protein coupled chemoattraction.

Fig. 7B shows regulation of chemoattraction by EphB2 reverse signaling. Purified cerebellar granule cells are chemoattracted to either SDF-1 or BDNF. EphB2-Fc inhibits the response to SDF-1, providing a mechanism for selective regulation of responsiveness to guidance factors.

25

### **Detailed Description of Specific Embodiments**

All references cited herein are incorporated in their entirety by reference.

Definitions. As used in this description and the accompanying claims, the  
5 following terms shall have the meanings indicated, unless the context otherwise requires:

Chemokine refers to small molecular weight proteins that regulate leukocyte migration and activation. They are typically secreted by activated leukocytes themselves, and also by stromal cells such as endothelial and epithelial cells, after inflammatory stimuli. Examples of chemokines include monocyte chemotactic protein (MCP)-3, MCP-  
10 4, macrophage inflammatory protein (MIP)-1 $\alpha$ , MIP-1 $\beta$ , RANTES (regulated on activation, normal T cell expressed and secreted), SDF-1, Teck (thymus expressed chemokine), and MDC (macrophage derived chemokine). As used herein, chemokine also includes any molecule that can act as a chemotactic agent. A chemotactic agent may be a small chemical compound, natural or synthetic, that is a selective agonist of a  
15 chemokine receptor, for example, CXCR4, a heterotrimeric G protein-coupled receptor (GPCR) that is the receptor for the chemokine SDF-1.

Altered cell migration means, within the context of the present invention, a measurable or observable effect on cell migration by an agent, when compared to cell migration in the absence of said agent.

20 Altered sensitivity to a chemokine means, within the context of the present invention, an effect of a chemokine on a population of cells that is measurably or observably different under one set of conditions (for example, in the absence of a PDZ-RGS3 protein) from the effect of the same chemokine on the same population of cells under a different set of conditions (for example, in the presence of a PDZ-RGS3 protein).



Chemokine-sensitive cell means a cell that shows a measurable or observable response to a chemokine, as defined above, in the context of cell migration.

A low molecular weight synthetic organic molecule means, within the context of the present invention, a synthetic chemokine.

5 Little is known of the specific effects of B ephrin reverse signaling on individual cells, or the signal transduction pathways that lead to such effects. The inventors have recently identified PDZ-RGS3 as a binding partner of B ephrins. In a *Xenopus* embryo de-adhesion assay, PDZ-RGS3 mediates signaling by the B ephrin cytoplasmic tail, in a manner dependent on both PDZ and RGS domains. Identification of the RGS protein led  
10 to further studies that identified a relationship between ephrins and chemokines. The inventors found that both SDF-1 and BDNF are *in vitro* chemoattractants for cerebellar granule cells. SDF-1 chemoattraction is selectively inhibited by soluble EphB receptor, and this inhibition is blocked by a truncated PDZ-RGS3 lacking the RGS domain. These results demonstrate a pathway connecting B ephrins to regulation of G protein coupled  
15 chemoattraction, and lead to a model for regulation of migration in cerebellar development.

Cell biological effects, and molecular mechanisms of ephrin-B reverse signaling, were characterized. In the course of their investigations, the inventors uncovered a novel pathway for extracellular control of heterotrimeric G proteins, and demonstrated selective  
20 regulation of responsiveness to guidance factors as a mechanism that can regulate neuronal migration.

Chemoattraction of a cell to another by chemokine stimuli can be modulated and/or regulated in cells by treatment with a PDZ-RGS3 type protein, wherein the PDZ-RGS3 type protein binds to a transmembrane protein such as B-ephrin, altering the cell's  
25 sensitivity to the chemokine. In the context of immune reactions such as autoimmune

disease, tissue rejection or allergy, the invention provides compositions and methods for altering leukocyte sensitivity to chemokines involved in such immune responses.

Modulation of chemokine signaling may also occur through the blocking of chemotaxis by ephrin reverse, and possibly forward, signaling. In such a pathway, soluble proteins comprising Eph receptor ectodomains may stimulate signaling through Eph receptors and interaction with the highly conserved PDZ-binding motifs. PDZ domains of various cell molecules including chemokines are known to also interact with the conserved PDZ-binding motifs. Introduction of soluble Eph receptor fusion proteins might thereby block the effect of chemokines or other G-protein coupled pathways involving molecules with PDZ domains that bind to the conserved PDZ-binding domains of the membrane proteins.

It has also recently been shown that tumor cells express a distinct, non-random pattern of functionally active chemokine receptors (Müller, et al., *Nature*, **410**, 50 (2001)). *In vitro*, chemokine ligand-receptor interactions trigger intracellular actin polymerization in leukocytes, a process that is prerequisite for cell motility and migration. Consistent with findings in leukocytes, CXCL12 (100 nM) and CCL21 (100 nM) induced, respectively, a transient 2.2- and 1.6-fold increase in intracellular filamentous actin (F-actin) in human breast cancer cells within 20 s. Conversely, the chemokine CX<sub>3</sub>CL1/fractalkine, whose receptor CX<sub>3</sub>CR1/V28 was not detected on breast cancer cells, did not induce actin polymerization.

In tumor cells, high levels of actin polymerization are required for the formation of pseudopodia, which in turn are needed for the invasion of malignant cells into tissues and for efficient metastases formation. Confocal laser scan microscopy of breast cancer cells stimulated in suspension with either CXCL12 or CCL21 revealed intense F-actin staining in the periphery of the cells and a redistribution of F-actin towards a leading

edge. In adherent breast cancer cells, distinct pseudopodia formation was observed after 20 min of stimulation with either CCL21 or CXCL12.

In agreement with these findings, both CXCL12 and CCL21 induced directional migration of breast cancer cells and directional invasion through a reconstituted basement  
5 membrane in a dose-dependent manner. Optimal migratory/invasive responses to CXCL12 or CCL21 were observed at concentrations of 100 nM, or 100 and 200 nM, respectively, reminiscent of observations made with leukocytes. Compared with breast cancer cells of well-characterized cell lines (MDA-MB-231, MDA-MB-361), primary tumor cells derived from a patient with malignant pleural effusion exhibited significant  
10 chemotactic responses to both CXCL12 and CCL21. CXCL12- and CCL21-mediated chemotaxis and invasion could be blocked by neutralizing anti-CXCR4 or anti-CCL21 antibodies, respectively, confirming the specificity of the chemotactic response induced by these chemokines.

Thus, signaling through CXCR4 or CCR7 mediates actin polymerization and  
15 pseudopodia formation in breast cancer cells, and induces chemotactic and invasive responses. In addition, it was found that organs representing the main sites of breast cancer metastasis are the most abundant sources of ligands for these tumor-associated receptors. *In vivo*, neutralizing the interactions of CXCL12/CXCR4 leads to a significant inhibition of lymph-node and lung metastasis.

20 In accordance with one embodiment of the present invention, there is provided a pharmaceutical composition comprising a soluble protein having an Eph receptor for delivering to a selected site an effective dose of said soluble protein, a suitable carrier, and optionally additional active or inert ingredients such as diluents, stabilizers, and excipients said soluble protein being capable of altering a cell signaling pathway. The

pharmaceutical composition is then administered to a patient with cancer, for inhibiting cell response pathways involving chemokine-mediated mechanisms in tumor metastasis.

The protein used in practicing the claimed invention may be a recombinant protein with an amino acid sequence identical to the claimed sequence of SEQ ID NO. 1, or a recombinant protein derived from SEQ ID NO. 1 but including modifications that change its pharmacokinetic properties while keeping its original B ephrin- (PDZ-) binding domain and its regulator of heterotrimeric G protein signaling- (RGS-) domain. The protein may also be a soluble protein or fusion protein of the Eph receptor domain comprising the conserved 33 amino acids of the C-terminus of the B ephrins – the PDZ-binding motif, a motif also found in many other cell surface molecules.

The mode of delivery of the protein may be by injection, including intradermal, intramuscular and subcutaneous, or topical, such as an ointment or patch. The protein may also be delivered as a nucleic acid sequence by way of a vector, such as a viral vector (e.g. adenovirus, poxvirus, retrovirus, lentivirus, or a Sindbis viral vector), or an engineered plasmid DNA.

Generally, the proteins of the presently claimed invention are administered as pharmaceutical compositions comprising an effective dose of the PDZ-RGS type protein or soluble Eph receptor domain in a pharmaceutical carrier. The protein can be combined for therapeutic use with additional active or inert ingredients, such as in conventional pharmaceutically acceptable carriers or diluents, along with physiologically innocuous stabilizers and excipients. A pharmaceutical carrier can be any compatible, non-toxic substance suitable for delivering the compositions of the claimed invention to a patient.

The quantities of reagents necessary for effective therapy will depend upon many different factors, including means of administration, target site, physiological state of the patient, and other medicaments administered. Thus, treatment dosages should be titrated

to optimize safety and efficacy. Animal testing of effective doses for treatment of particular cancers or disease states such as autoimmune or allergic response will provide further predictive indication of human dosage. Pharmaceutically acceptable carriers will include water, saline, buffers, and other compounds described, for example, in *the Merck Index*, Merck & Co., Rahway, NJ. Slow release formulations, or a slow release apparatus  
5 may be used for continuous administration.

Dosage ranges for the claimed proteins would normally be expected to be in amounts lower than 1 mM concentrations, typically less than about 10  $\mu$ M concentrations, usually less than about 100 nM, and particularly less than about 10 pM  
10 and more particularly less than about 1 fM, with an appropriate carrier. Treatment is normally initiated with smaller dosages which are less than optimum, and from there, the dosage is increased by small amounts to achieve the optimum effect under the circumstances. Determination of the ideal dosage and administration protocol for a particular patient or situation will be readily identified by one with ordinary skill in the  
15 art.

It has been shown by the inventors that a cytoplasmic protein containing a PDZ domain and an RGS domain is capable of binding to B ephrins through the PDZ domain and mediating signaling from the cytoplasmic tail of the B ephrin. The signal mediation is dependent on both the PDZ and the RGS domains. Chemokines such as SDF-1, also  
20 known as SDF-1 $\alpha$ , and BDNF, typically associated with leukocyte migration, herein act as chemoattractants for cerebellar granule cells. The inventors found that the chemokine SDF-1 is selectively inhibited by the presence of soluble EphB receptor but that this inhibition is blocked by a truncated PDZ-RGS type protein lacking the RGS domain, suggesting a connection between B ephrins and regulation of G protein-coupled  
25 chemoattraction. Effects of the presently claimed proteins on immune response or cell

migration could be monitored by a number of different methods. For example, measuring an immune response, whether enhanced or inhibited, to antigen-specific stimulation of immunoglobulin levels in serum, typically known as B-cell response, could be done in the presence or absence of the claimed proteins. In addition, a similar analysis for an  
5 increase or decrease in specific immunoglobulins associated with T cells is possible.

In accordance with one embodiment of the present invention, the proteins claimed herein could be used in cancer treatment, or to treat autoimmune and/or allergic responses and diseases. An altered immune response is thus measured or observed by analyzing an antigen-specific cytotoxic response of defined population of lymphocytes such as those of  
10 the blood, spleen, lymph nodes, or a tumor. Other means for monitoring the effect of a PDZ-RGS type protein include analysis of rates of tumor metastasis, or tumor growth, or an increase or decrease in tumor incidence in a patient or animal model or cell population.

Additional diseases or medical conditions envisioned to be appropriate systems  
15 for monitoring altered cell migration such that ephrin signaling will provide therapeutic benefit in inflammatory and autoimmune diseases include: arthritis (including osteoarthritis and rheumatoid arthritis), inflammatory bowel disease, Crohn's disease, emphysema, acute respiratory distress syndrome, asthma, chronic obstructive pulmonary disease, Alzheimer's disease, organ transplant toxicity, cachexia, allergic reactions,  
20 allergic contact hypersensitivity, cancer, tissue ulceration, restenosis, periodontal disease, epidermolysis bullosa, osteoporosis, loosening of artificial joint implants, atherosclerosis (including atherosclerotic plaque rupture), aortic aneurysm (including abdominal aortic aneurysm and brain aortic aneurysm), congestive heart failure, myocardial infarction, stroke, cerebral ischemia, head trauma, spinal cord injury, neurodegenerative disorders  
25 (acute and chronic), Huntington's disease, Parkinson's disease, migraine, depression,

peripheral neuropathy, pain, cerebral amyloid angiopathy, amyotrophic lateral sclerosis, multiple sclerosis, ocular angiogenesis, corneal injury, macular degeneration, abnormal wound healing, burns, diabetes, tumor invasion, tumor growth, tumor metastasis, corneal scarring, scleritis, AIDS, sepsis, septic shock, and other conditions characterized by

5 hyperinflammatory states and autoimmune dysfunctions.

In accordance with one embodiment of the present invention, the proteins or protein fragments claimed herein could be formulated alone or in combination with substances for slow release at a delivery site. Alternatively, they could be formulated as fusion proteins or constructs made by chemical ligation of a PDZ-RGS type protein or

10 protein fragment and a targeting moiety, or of an Eph receptor ectodomain type protein and a targeting moiety, thus allowing delivery of the construct to tumors of interest (for example, the targeting moiety could be an antibody or fragment of antibody, or a protein ligand, or a peptide of more than about 10 amino acids). Similarly, they could be formulated as a DNA or viral vector (for example, a Sindbis vector) encoding the protein

15 or protein fragment with or without a targeting moiety.

### EXAMPLES

The claimed invention may be illustrated by the following non-limiting examples, which are more easily understood by reference to the following experimental details.

#### 20 Plasmids and antibodies

GST fusions were in vector pGEX2T (Pharmacia), and plasmids for cell transfection or embryo injection in vector CS2(+) (Rupp et al., 1994). *In situ* probes were: full length ephrin-B 1 cDNA (Davis et al., 1994); XbaI/XhoI fragment of ephrin-B2 (Bergemann et al., 1995); nucleotides 3 to 861 of PDZ-RGS3; HindIII/PstI

25 fragment of ephrin-B3 (Bergemann et al., 1998); nucleotides 2698 to 3104 of EphB2

(Henkemeyer et al., 1996); nucleotides 2139 to 2873 of EphB3 (Ciossek et al., 1995); or CXCR4 and SDF-1 probes as described (Suzuki et al., 1999). Myc-SAP97 and myc-PSD95 plasmids were gifts from Dan Pak and Morgan Sheng. Rabbit polyclonal anti-PDZ-RGS3 antibodies were raised against an internal peptide

- 5    TIPEEPGTTTKGKSYT or the C-terminal peptide RSDLYLINQKKMSPPL, with an N-terminal cysteine added for conjugation with carrier KLH. Antiserum was affinity purified on peptide columns using SulfoLink kit (Pierce). Antibodies to both peptides detect PDZ-RGS3 in Western blots of transfected cells and tissues. Rat monoclonal anti-HA was from Boehringer Mannheim. Mouse monoclonal anti-Myc, rabbit
- 10   anti-ephrin-B1 (A20), rabbit anti-ephrin-B (C18) and goat anti-CXCR4 (C20) were from Santa Cruz Biotechnology.

#### **Yeast two-hybrid screen and cDNA cloning**

- A two-hybrid library, a gift from Stanley Hollenberg, was screened as described (Hollenberg, et al., 1995). Several clones with overlapping partial sequences of
- 15   PDZ-RGS3 were obtained. The longest contained nucleotides 15 to 465 and was used to probe a mouse newborn brain cDNA library (Stratagene). Among several overlapping clones, the longest contained nucleotides 1 to 1421. To obtain full length cDNA, 3' RACE was performed on mouse E15.5 Marathon cDNA (Clontech) using 5' internal primer set gTgggcaagcgagtgccagcacaccctg and ccgcacatcccgcattccagttacggcacc.

- 20   Multiple RACE clones were sequenced to ensure fidelity.

#### **GST pull-down, immunoprecipitation and Western blot**

GST fusions expressed in strain BL21 were immobilized on glutathione beads (Sigma). Twenty-five-μL beads were incubated with 25-50 μL <sup>35</sup>S-labeled PDZ-RGS3 made by *in vitro* transcription and translation (Promega TNT kit), in 500 μL binding



buffer (25 mM TrisHCl 7.4, 150 mM NaCl, 1 mM EDTA and 1 mM DTT). Beads were washed with binding buffer followed by SDS-PAGE and autoradiography.

For immunoprecipitations, COS cells were Lipofectamine transfected (Gibco) and lysed 30 hr later (25 mM Tris-HCl 7.4, 150 mM NaCl, Boehringer protease inhibitor cocktail, 1 mM DTT and 1% Triton X-100). After-microfuge clearing, supernatants were incubated with antibodies 1 hr, then protein A sepharose beads (Pharmacia) 1 hr. Beads were washed with lysis buffer, proteins were resolved on SDS gels, and transferred to PVDF membranes (Gelman Sciences).

Mouse E16.5 cerebral cortices were triturated with a blue Gilson tip in hypotonic buffer (25 mM Tris-HCl 7.4, protease inhibitor cocktail, 1 mM DTT). After 10 min on ice, cells were lysed by passing through a 27-gauge needle 4-6 times. After microfuging 5000 rpm, 5 min, supernatant containing membranes and cytosol was incubated with 1% Triton X-100, 150 mM NaCl, 10 min on ice before immunoprecipitation as above.

#### **Xenopus embryo de-adhesion and granule cell migration assays**

For the Xenopus assay, plasmids were *NotI* linearized and transcribed to capped mRNA by SP6 mMessage mMachine kit (Ambion). Two-cell embryos were injected, and screened for de-adhesion as described (Jones et al., 1998). For each plasmid combination, protein levels were tested by Western blot and were consistent. Approximately 30 embryos were tested for each condition in each experiment, and experiments were repeated 3 to 5 times with consistent results. Data shown are averages of all results combined.

For migration assays, granule cells from P8-P9 mouse cerebella were dissociated and purified as described (Hatten, 1985) with modifications. Briefly, the cell suspension was spun 20 min, 3500 rpm on a step gradient (60% and 35% isotonic Percoll). The second layer of cells was collected, washed, and resuspended in NB medium

(Neurobasal/B27; Gibco). Purified cells were incubated 37°C on a poly-D-lysine coated culture flask, then shaken off after 2 hr for the migration assay. The cells were found to need this recovery period, perhaps for restoration of ephrin-B1 expression after trypsin cleavage.

5 Transwell membranes (polycarbonate, 5 micron pores; Costar) were pre-coated on both sides with laminin (20 µg/mL) • 1 hour then PBS washed. BDNF (Peprotech), SDF-1 (also called SDF-1α; Peprotech or Calbiochem) and EphB2-Fc were found most effective at concentrations of 10 ng/mL, 100 ng/mL, and 2 µg/mL, respectively, in line with previous publications. 100,000 cells were placed in the top chamber and incubated  
10 37°C, 5% CO<sub>2</sub>, 16 hr. The membrane was then methanol fixed and Giemsa stained. The upper side was wiped off, and cells that had migrated and attached to the lower side were counted blind, in 4 central fields with a 16X objective. Each condition was tested in duplicate or triplicate per experiment, and each experiment repeated 3 to 5 times with consistent results. Data shown are averages of all results combined.

15 For viral transduction, PDZ-RGS3<sup>PDZ-EGFP</sup> was cloned into pSinRep5 (Invitrogen), and virus produced by the manufacturer's instructions. Immediately after the 2 hr recovery of purified granule cells, EGFP or PDZ-RGS3<sup>PDZ-EGFP</sup> virus, with a similar titer, were added. Infection was 1 hr, room temperature on an orbital shaker, then 1 hr at 37°C. The assay was as above, except migration was for only 6 hr, then membranes  
20 were fixed with 4% paraformaldehyde in PBS 10 min, washed once with PBS, and slide mounted with fluoromount-G (Southern Biotechnology).

### Immunocytochemistry

COS cells transfected with HA-ephrin-B1 and myc-PDZ-RGS3 were fixed in 4% paraformaldehyde, 4% sucrose in PBS, incubated with C18 antibody and monoclonal  
25 anti-myc in 0.5% NP40, 5% BSA in PBS, 1 hr, then secondary antibodies for 1 hr (donkey

anti-rabbit-Rhodamine RedX and donkey anti-mouse-FITC; Jackson Immunoresearch) and mounted in Fluoromount-G.

Purified granule cells were cultured overnight on laminin (100 µg/mL) pre-coated coverslips. EphB2-Fc (5 µg/) was added, 30 min, 37°C. Cells were fixed 15 min in 4% paraformaldehyde, 4% sucrose in PBS, permeabilized 5 min, 0.25% TritonX-100, blocked 2 hr, 10% BSA in PBS, labeled 4°C overnight with rabbit anti-human Fc plus goat anti-CXCR4, or goat anti-human Fc (Jackson Immunoresearch) plus rabbit anti-PDZ-RGS3 in 3% BSA in PBS, then 2 hr, room temperature with secondary antibodies (donkey anti-goat-FITC and donkey anti-rabbit-Rhodamine RedX) and mounted in ProLong Antifade (Molecular Probes).

Immunocytochemistry using purified leukocyte cells is done as with granule cells. The purified leukocytes are cultured overnight, using standard techniques known to those skilled in the art. Addition of EphB2-Fc and labeling with anti-human Fc plus goat anti-CXCR4, or goat-anti-human Fc plus rabbit anti-PDZ-RGS3 with secondary antibodies is as described above for granule cells.

### Example 1

#### Investigation of Reverse Signaling by B ephrin

##### Identification of B ephrin binding proteins

As a first step to dissect reverse signaling, identification of B ephrin binding proteins was undertaken. Yeast two-hybrid cloning was employed, screening a mouse embryonic cDNA library (Hollenberg, et al., 1995) with the entire cytoplasmic domain of ephrin-B2 as bait. Subsequent studies focused on one of the cDNAs identified, encoding a previously unidentified 930 amino acid protein sequence (Figure 1). Two motifs were identified in this sequence, a PDZ domain at the N-terminus, and an RGS domain at the C-terminus. The initial screen identified a subfragment containing the PDZ domain, and

the rest of the cDNA was then assembled by library screening and polymerase chain reaction (see experimental detail, above). The linkage of PDZ and RGS domains in the same molecule in mouse tissues was confirmed by Northern blot, Western blot and *in situ* hybridization (experimental procedures and data not shown).

5 Database searching revealed no identical sequence. However, it did reveal strong homology of the C-terminal half of this mouse sequence to human RGS3, which was previously described as a shorter sequence (Figure 1). Like human RGS3 (Druev et al., 1996), the PDZ-RGS protein identified here can inhibit G protein mediated MAP kinase activation in transfected cells (data not shown) confirming its GAP activity. While it is  
10 not known definitively whether the mouse and human proteins have a direct ortholog relationship, in view of the close homology within their RGS domains the newly identified protein has been called PDZ-RGS3.

#### Binding of PDZ-RGS3 to B ephrins

After identifying PDZ-RGS3, the results of the two-hybrid screen were  
15 investigated to determine whether they reflect a biologically meaningful interaction. To address this, binding between PDZ-RGS3 and B ephrins was tested, using several approaches.

##### 1. *In vitro* GST fusion protein pull-down assay.

Fusion proteins were constructed between GST and the C-terminal 33 amino acids  
20 of ephrin-B1 (identical to the same region of ephrin-B2). In addition to the wild type sequence (GST-ephrin-B 1), a version was made with the C-terminal Valine replaced by Alanine (GST-ephrin-B1<sup>V/A</sup>), which is expected to abolish or strongly reduce binding of PDZ proteins (Song yang et al., 1997). Affinity beads bearing GST-ephrin-B1 or GST-ephrin-B1<sup>V/A</sup> in similar amounts (Figure 2A, lanes 10-11) were used to bind  
25 <sup>35</sup>S-labelled wild type or truncated PDZ-RGS3. GST-ephrin-B1 interacted specifically

with PDZ-RGS3 (Figure 2A, lane 3), whereas GST-ephrin-B1<sup>V/A</sup> did not (Figure 2A, lane 2). The PDZ domain of PDZ-RGS3 was both necessary (Figure 2A, lanes 4-6) and sufficient (Figure 2A, lanes 7-9) for this binding. These results indicate a direct interaction between the PDZ binding motif in the ephrin-B cytoplasmic domain, and the PDZ domain of PDZ-RGS3.

## 2. Binding in transfected cells.

Constructs encoding myc-tagged PDZ-RGS3 and HA-tagged ephrin-B1, or mutant derivatives, were co-transfected into COS cells. Lysates were then immunoprecipitated with anti-myc or anti-HA, followed by Western blot using anti-myc or a rabbit polyclonal anti-ephrin-B. Levels of wild-type and mutant proteins were comparable (Figure 2B, lanes 4-6). Wild type ephrin-B1 and PDZ-RGS3 interacted, regardless of which was initially precipitated (Figure 2B). This interaction was impaired by the ephrin-B1<sup>V/A</sup> mutation (Figure 2B, lanes 2 and 5) and by removing the last 3 amino acids, which form most of the PDZ binding motif (ephrin-B 1<sup>A3</sup>, Figure 2B, lanes 3 and 6). As controls, ephrin-B 1 did not co-precipitate with SAP97 (Figure 2B, lanes 7-10) or PSD95 (not shown), two PDZ proteins implicated in synapse assembly (Sheng and Pak, 2000). When fixed cells were stained for epitope-tagged PDZ-RGS3 and ephrin-B1, the two staining patterns co-localized closely (Figure 2D). Treating the cells with a soluble EphB2-Fc fusion protein did not appear to either enhance or inhibit subsequent coprecipitation of ephrin-B1 and PDZ-RGS3 (data not shown). These results indicate constitutive binding between PDZ-RGS3 and ephrin-B1 in transfected mammalian cells.

## 3. Interaction in lysates of a neuroblastoma cell line, or mouse cortex, where PDZ-RGS3 and ephrin-B 1 are expressed endogenously.

Ephrin-B 1 was immunoprecipitated with a rabbit polyclonal antibody, and the subsequent Western blot was probed with an antibody to PDZ-RGS3. The results show

that a PDZ-RGS3immunoreactive protein of the expected size co-precipitated with ephrin-B1 (Figure 2C, lanes 1 and 2), indicating an interaction between PDZ-RGS3 and ephrin-B1 endogenously expressed in neural cells and tissues.

5    Overlapping expression of PDZ-RGS3 and B ephrins

          If PDZ-RGS3 and B ephrins interact functionally, it is expected they will have overlapping expression patterns. Therefore, comparison of PDZ-RGS3 expression with that of ephrin-B1 and ephrin-B2 by *in situ* hybridization on mouse embryos was carried out. PDZ-RGS3 co-localized with ephrin-B1 in cortical ventricular zone (Figures 3A and 10 3B), with ephrin-B2 in early cerebellar primordium (Figures 3C and 3D), with both ephrin-B1 and -B2 in dorsal root ganglia (Figures 3E and 3F) and with ephrin-B1 or -B2 in several other tissues (not shown). Taken together, the binding data described above and the closely overlapping expression patterns indicate that PDZ-RGS3 is a genuine biological interaction partner of B ephrins.

15

B ephrin signaling in *Xenopus* embryos mediated by PDZ-RGS3

          The functional relationship between B ephrin and PDZ-RGS3 was next examined. Microinjection of ephrin-B1 RNA was previously shown to cause cell de-adhesion in *Xenopus* embryos or animal caps. The C-terminal 19 amino acids were required, whereas 20 the extracellular domain was not (Jones, et al., 1998), showing this phenotype involves interactions of the ephrin-B1 cytoplasmic tail, and is not dependent on forward signaling. (Signaling by B ephrin lacking an extracellular domain is consistent with the constitutive signaling seen when other receptors are truncated.) This assay has the advantage that it permits multiple proteins to be expressed simultaneously and at variable levels, 25 facilitating analysis of domain functions and interactions.

1. Requirement of the PDZ binding domain of ephrin-B1 for the de-adhesion activity.

Ephrin-B1<sup>Δ3</sup> did not cause the de-adhesion phenotype (Figure 4) showing the PDZ binding motif is required. Next, a mutant PDZ-RGS3 without the PDZ domain (PDZ-RGS3<sup>ΔPDZ</sup>) was tested. PDZ-RGS3<sup>ΔPDZ</sup>, alone or together with ephrin-B1, had no  
5 evident effect on the assay (Figure 4), showing the PDZ domain of PDZ-RGS3 is also required.

2. PDZ-RGS domain effects on ephrin-B1 de-adhesion activity.

Ephrin-B1 RNAs were next co-injected with various forms of PDZ-RGS3. The first form of PDZ-RGS3 tested had the RGS domain deleted (PDZ-RGS3<sup>ΔRGS</sup>), to create a  
10 putative dominant negative protein. PDZ-RGS3<sup>ΔRGS</sup> alone had no effect. However, it inhibited the cell dissociation caused by ephrin-B1 in a dose dependent manner (Figure 4). In principle, such an effect by this dominant negative protein could be to block the access of any PDZ domain-containing protein in the cell. Thus, ephrin-B1 was next co-expressed together with full length PDZ-RGS3. In this experiment, ephrin-B1 was added  
15 at a level suboptimal for dissociation, and full-length PDZ-RGS3 was found to increase dissociation in a dose-dependent manner (Figure 4). Injection of full-length PDZ-RGS3 alone, as a control, did not cause dissociation (Figure 4). These results indicate that PDZ-RGS3 can mediate the effect of the ephrin-B1 cytoplasmic tail, and also show the RGS domain is required.

20 3. Investigation of membrane-localization of PDZ-RGS3 using PDZ-RGS3 with an added myristoylation motif (PDZ-RGS3<sup>myr</sup>).

Most, if not all, the protein from this construct localized to the membrane fraction, whereas wild-type PDZ-RGS3 expressed by itself was mainly cytosolic (data not  
25 shown). Embryos injected with PDZ-RGS3<sup>myr</sup> did not develop the de-adhesion phenotype (Figure 4). This indicates that localizing PDZ-RGS3 to the membrane is not sufficient, and therefore suggests the requirement for ephrin-B1 is not simply to bring

PDZ-RGS3 to the membrane. The results in the *Xenopus* assay show PDZ-RGS3 can mediate signaling induced by ephrin-B1, and that this requires both PDZ and RGS domains.

## Example 2

5                   Correlated expression patterns in cerebellar development and possible mechanism for reverse signaling.

### Effect of soluble EphB receptor on isolated cells and its role in neuronal guidance.

Identification of PDZ-RGS3, and the demonstration of a role for its RGS domain  
10   in the *Xenopus* assay suggested that one potential mechanism of reverse signaling could be to regulate signaling by a GPCR. If so, B ephrins should be expressed in the same regions as candidate GPCRs. Consequently, the expression of ephrin-B2 and EphB2 in cerebellar granule cells was of particular interest. In mice with gene disruption of SDF-1 or its receptor CXCR4, granule cells migrate prematurely from the external granule cell  
15   layer (EGL), indicating SDF-1 normally functions to prevent premature inward migration (Ma et al., 1998; Zou et al., 1998).

To investigate these ideas further, expression patterns were examined by *in situ* hybridization. Granule cell migration normally begins around postnatal day 3 (P3) and continues into the third postnatal week (flatten, 1999). Expression of SDF-1 and CXCR4  
20   has been reported at pre-natal stages (Zou et al., 1998; McGrath et al., 1999), and we extended this postnatally. Consistent with the prenatal pattern, we saw RNA expression for CXCR4 in the EGL, while SDF-1 was restricted more superficially to the pial membrane. Similar patterns were seen at P0 and P3 (Figure 5A), and P6 (not shown). Ephrin-B2 was expressed in the EGL at P3, though this expression was not readily  
25   detectable at P0 (Figure 5A). EphB2 receptor was also found in the EGL, with weak expression at P0 and strong expression at P3 (Figure 5A).



Co-expression of B ephrin and CXCR4 was confirmed in individual purified granule cells (Figure 5B). If PDZ-RGS3 is to mediate B ephrin reverse signaling in granule cells, these two molecules must also be expressed in the same cells. This was addressed by immunofluorescence staining, showing purified granule cells stain with antibodies to both PDZ-RGS3 and B ephrins (Figure 5B). The species origin of these antibodies precluded co-staining, so subcellular co-localization was tested in cells that were first treated unfixed with EphB2-Fc, and subsequently permeabilized and stained with anti-PDZ-RGS3 and anti-Fc. Co-localization was seen in patches located on the cell body and cell processes (Figure 5C). Additional staining may represent protein that is free, or associated with other binding partners, or located in intracellular compartments inaccessible to EphB2-Fc.

#### Regulation of cerebellar granule cell chemoattraction

To test functionally for an interaction of ephrin-B and SDF-1, a Transwell assay system was assembled using purified cerebellar granule cells. Briefly, a membrane filter with defined uniform pore size separates upper and lower chambers. Cells are placed in the upper chamber and the number of cells that have migrated to the lower side of the filter is subsequently counted.

Initially, a chemoattractant effect of SDF-1 on cultured granule cells was investigated, something which had not been described previously. When SDF-1 was added to the lower chamber it promoted migration of granule cells ( $p < 0.001$ , unpaired t test; Figure 6A). Reverse signaling was triggered with soluble EphB2-Fc, which is dimerized by its Fc tag and used without further clustering (Bruckner et al., 1997). Addition of EphB2-Fc with the cells in the top chamber inhibited the chemoattractant effect of SDF-1 ( $p < 0.001$ ; Figure 6A). Inhibition was also seen, though to a lesser degree, when EphB2 was added to the bottom chamber (not shown). Control Fc protein

had no detectable effect (Figure 6A). When EphB2-Fc was added to the top or bottom chambers in the absence of SDF-1, there was no detectable change from background levels of migration (Figure 6A). Therefore, while this assay provided no evidence that EphB2-Fc itself acted as an attractant or repellent, it inhibited chemoattraction to SDF-1.

5        A potential explanation for this inhibitory effect of EphB2-Fc, not intended to be limiting in any way, could be a general effect on cell motility or responsiveness. To address this, we tested BDNF as a control attractant. BDNF was previously reported to promote cerebellar granule cell survival (Schwartz et al., 1997), and since it can act *in vitro* as an attractant for axons (Song et al., 1997) it was considered likely that it might  
10        also act as a chemoattractant for granule cells. Addition of BDNF to the lower chamber indeed promoted migration ( $p < 0.005$ ; Figure 6B). Addition of EphB2-Fc to the top or bottom chamber did not inhibit cell migration towards BDNF (Figure 6B). Thus, the inhibition by EphB2-Fc was selective for SDF-1 induced migration.

      These results supported the prediction, based on analysis of PDZ-RGS3, that  
15        reverse signaling might affect a heterotrimeric G protein signaling pathway. To assess this further, a dominant negative form of PDZ-RGS3 was tested. To overcome a major obstacle for such an experiment, namely, the difficulty of expressing genes with high enough efficiency in primary neurons, a Sindbis viral vector was used, based on reports of efficient gene transfer into a wide variety of cells. Enhanced green fluorescent protein  
20        (Chalfie et al., 1994) was incorporated into the constructs, so infected cells could be traced. The dominant negative construct in these experiments was the PDZ domain of PDZ-RGS3, fused to EGFP (PDZ-RGS3<sup>PDZ-EGFP</sup>). As in uninfected cells, when granule cells were infected with control EGFP virus, SDF-1 acted as a chemoattractant, and thus was inhibited by EphB2-Fc (data not shown). When PDZ-RGS3<sup>PDZ-EGFP</sup> was introduced

into the cells, SDF-1 still acted as a chemoattractant ( $p < 0.001$ ; Figure 6C). However, the inhibitory effect of EphB2-Fc on this chemoattraction was now blocked (Figure 6C).

### Example 3

#### 5                   Effect of PDZ-RGS3 on Leukocyte Migration

##### Effect of soluble EphB receptor on isolated cells and its role in leukocyte migration.

As stated above, identification of PDZ-RGS3, and the demonstration of a role for its RGS domain in the *Xenopus* assay suggested that one potential mechanism of reverse signaling was to regulate signaling by a GPCR (G protein-coupled receptor). Recently, 10   Wu et al., Nature, 410, 948 (2001), showed that the secreted protein Slit, previously known for its role of repulsion in axon guidance and neuronal migration, also inhibited leukocyte chemotaxis induced by chemotactic factors, i.e. chemokines.

##### Regulation of cerebellar granule cell chemoattraction

To investigate this concept with PDZ-RGS3 protein, a transwell system is 15   assembled wherein the effect of leukocyte migration, in the presence of an appropriate chemokine such as SDF-1 with or without PDZ-RGS3 protein, is monitored.

To test functionally for an interaction of the GPCR ephrin B and SDF-1, a transwell assay system can be assembled using purified leukocytes. As described above, a membrane filter with defined uniform pore size separates upper and lower chambers. 20   Cells are placed in the upper chamber and the number of cells that have migrated to the lower side of the filter is subsequently counted.

Initially, the chemoattractant effect of an appropriate chemokine, such as SDF-1, on cultured leukocyte cells is investigated. The chemokine is added to the lower chamber to promote migration of leukocyte cells. Reverse signaling is then triggered with soluble 25   EphB2-Fc, which is dimerized by its Fc tag and used without further clustering as above.

EphB2-Fc is then added with the cells in the top chamber to look for inhibition of the chemoattractant effect of the chemokine, in this case, SDF-1. Control Fc protein is also added to the top chamber, and expected to have no effect.

BDNF can also be added to the chambers as a control attractant, to investigate any  
5 general effect on cell motility of responsiveness exhibited by EphB2-Fc, and to determine whether the effect on migration of leukocytes by the assayed chemokine, in this case SDF-1, is selective. If addition of EphB2-Fc to the top or bottom chamber does not inhibit cell migration towards BDNF, then inhibition by EphB2-Fc will be selective for the chemokine (SDF-1) induced migration observed.

10

#### Example 4

##### Another possible Function of PDZ-RGS3

A second potential function for transmembrane ligands is to allow bi-directional  
15 signaling. Again, the ephrins have provided a particularly good model system to investigate this idea. Reverse signaling through B ephrins has been demonstrated biochemically by ligand phosphorylation. Evidence of important developmental roles has come from genetic and embryological studies of whole embryos or tissues. Herein, characterization of cell biological effects, and molecular mechanisms of ephrin-B  
20 reverse signaling, have been detailed. In addition, the experiments have led to other conclusions, uncovering a novel pathway for extracellular control of heterotrimeric G proteins, and demonstrating selective regulation of responsiveness to guidance factors as a mechanism that can regulate neuronal migration.

Molecular and cellular mechanisms of reverse signaling

Reverse signaling at a molecular level was investigated by screening for proteins that bind the B ephrin cytoplasmic domain, leading to identification of PDZ-RGS3 in a yeast two-hybrid assay. The two proteins also bind one another in an *in vitro* GST pull-down assay, and by co-immunoprecipitation from lysates of transfected cells, or 5 neural cells and tissues that express the two proteins endogenously. *In situ* hybridization shows a close overlap of expression patterns for PDZ-RGS3 with one or other of the three known B ephrins in several parts of the nervous system. Taken together these results indicate that PDZ-RGS3 is a genuine biological interaction partner of B ephrins.

10 The domain structure of PDZ-RGS3 suggests how this protein might function, but the following is in no means intended to be limiting of function. PDZ domains are known to bind to a short conserved motif at the C-terminus of many membrane proteins (Songyang et al., 1997; Sheng and Pak, 2000). A sequence fitting this motif is found at the C-terminus of all known B ephrins, and the experiments herein indicate that the PDZ 15 domain of PDZ-RGS3 binds the ephrin-B C-terminus. Tyrosine residues are found in the binding motif (YYKV-carboxy terminus) suggesting potential control of binding by phosphorylation, and the PDZ-RGS3/ephrin B interaction did not appear to be regulated by EphB receptor binding. The presence of an RGS domain suggested PDZ-RGS3 might interact with downstream effector pathways. In fact, a *Xenopus* embryo cell dissociation 20 assay showed that PDZ-RGS3 mediates effects of the B ephrin cytoplasmic tail, in a manner dependent on both its PDZ and RGS domains. While the *Xenopus* assay was well suited to test the function and interaction of individual domains, such a system does not readily assess the effect of Eph receptor binding, the downstream pathways, and the relevance to guidance. Due to the involvement of the RGS domain in signaling, as well 25 as the cerebellar expression of ephrins, cerebellar granule cells were tested for an effect

of reverse signaling on the action of SDF-1, which acts through a GPCR. As expected, soluble EphB2-Fc selectively regulated the guidance response to SDF-1, and this regulation was blocked by a truncated version of PDZ-RGS3 lacking the RGS domain. A molecular model based on such studies, in no way intended to be the only possible model, is shown in Figure 7A.

At the level of cell biological effects, the above examples show that reverse signaling induced by Eph receptor can regulate cellular guidance (Figure 7B). Specifically, soluble EphB2-Fc selectively inhibited SDF-1 chemoattraction of cultured cerebellar granule neurons. Although reverse signaling through B ephrins has been investigated more extensively, soluble EphA receptors can affect adhesion in cell lines (Huai and Drescher, ; Davy et al., 1999), and it will be interesting to see if this may reflect similar developmental functions or signaling pathways. The above data on the regulation of cerebellar granule cell guidance by EphB2-Fc, SDF-1, and BDNF suggests a model, in no way intended to be the only model, for control of cell migration in cerebellar development, as described further below. It is envisioned, in fact, that the above observations also fit with other developmental functions proposed for B ephrin reverse signaling, in blood vessel formation, rhombomere compartmentation, and axon pathway selection, all involving regulation of migration or morphogenesis.

Regarding the mechanism for signal transduction across the cell membrane, as with other PDZ proteins that bind B ephrins (Torres et al., 1998; Bruckner et al., 1999; Lin et al., 1999), the association with PDZ-RGS3 was seen constitutively, and did not appear to be modulated by treating cells with soluble EphB2-Fc. This suggests regulated association between B ephrin and PDZ-RGS3 is not a likely mechanism of signal transduction. An alternative could be regulation of clustering or subcellular localization. It is known that EphB2-Fc can cluster B ephrins and associated PDZ proteins into

membrane rafts (Bruckner et al., 1999). Heterotrimeric G proteins have also been localized to rafts (Simons and Ikonen, 1997). Therefore, one model could be that Eph receptor binding could cluster B ephrins into rafts, or other subcellular structures, and this could bring associated PDZ-RGS3 into proximity with the appropriate G proteins, resulting in inhibition of their activity. It is finally worth noting that not only the PDZ binding motif, but at least 33 amino acids of the B ephrin cytoplasmic tail are strongly conserved, and it is likely that additional protein interactions play a role in signaling, either through independent pathways or in collaboration with PDZ-RGS3.

#### Heterotrimeric G protein signaling

Heterotrimeric G proteins are classically controlled by receptors in the seven--transmembrane family. RGS proteins were identified as GAPs for G proteins, and contain additional protein modules, including PDZ domains, which could potentially allow control of G proteins by other signaling pathways. Moreover, PDZ and RGS domains can associate through protein-protein interactions, as in the case of GIPC/NIP/SEMCAP-1, a PDZ protein that binds the RGS protein GAIP, and also interacts with cell surface semaphorins and neuropilins (De Vries et al., 1998; Cai and Reed, 1999; Wang et al., 1999). The observation that B ephrin signaling can be mediated by PDZ-RGS3, in a manner requiring both PDZ and RGS domains, provides a possible explanation, in no way intended to be limiting, for the presence of both PDZ and RGS domains in this protein. The regulation of a G protein pathway by ephrin reverse signaling also provides a potentially general mechanism that can allow heterotrimeric G protein pathways to be regulated through cell surface receptors, other than classical seven-transmembrane GPCRs.

It is not clear to what degree PDZ-RGS3 interactions might be general or specific.

Most known RGS proteins, including human RGS3, are GAPs for the  $G_{\alpha i}$  or  $G_{\alpha q}$

subfamily of G proteins. Our results are therefore very consistent with studies showing CXCR4 is coupled to G $\alpha$ i2 (Moepps et al., 1997). On the other hand, experiments on purified proteins or transfected cells suggest the specificity of RGS proteins for individual G proteins, and likewise the specificity of PDZ proteins for individual binding motifs, may not be high. Differences in affinity or kinetics could provide some degree of specificity. Alternatively, biological specificity may come from expression patterns, since these intracellular interactions would require the proteins to be expressed in the same cell. In keeping with this idea, we find a close correlation in the expression patterns of PDZ-RGS3 and B ephrins, suggesting there may be a special biological relationship between these proteins. Finally, a further layer of specificity could be provided by subcellular localization. The observation that PDZ-RGS3 failed to signal when targeted to the membrane by myristoylation could be consistent with a model where B ephrins not only bring PDZ-RGS3 to the membrane, but also target it to signaling complexes containing the appropriate G proteins.

#### 15 Cerebellar granule cell migration

The inward migration of cerebellar granule cells from the EGL is one of the best characterized models of neuronal migration. The genetic demonstration that SDF-1 and its receptor CXCR4 are required for normal granule cell migration provided the first evidence of chemokines as regulators of neural development. Specifically, the phenotype of premature granule cell migration, taken together with the embryonic expression of SDF-1 in the pia mater overlying the cerebellum, suggested a model wherein SDF-1 prevents premature inward migration of cerebellar granule cells by chemoattraction toward the pia (Ma et al., 1998; Zou et al., 1998; McGrath et al., 1999). The presently claimed invention supports this model, by experimental results showing SDF-1



expression in the pia at postnatal stages that span the onset of granule cell migration, and by demonstrating that SDF-1 is a chemoattractant for cultured cerebellar granule cells.

Experiments further show that reverse signaling induced by soluble EphB2-Fc can inhibit the effect of SDF-1 on cerebellar granule cells. This provides the first functional  
5 evidence for an effect of ephrin signaling on cerebellar granule cells. A developmental role for the interaction of these signaling pathways is supported by the correlated expression of ephrinB2, SDF-1, and their receptors during cerebellar development.

The following model is based on the above functional assays of primary cultured cerebellar granule cells, the expression patterns of the relevant molecules during  
10 cerebellar development, and the phenotypes of SDF-1 and CXCR4 gene disrupted mice. During the period when some granule cells remain in the EGL, and others have migrated inwards, expression of SDF-1 and CXCR4 persists. To reconcile the inconsistency that SDF-1 prevents inward migration by chemoattracting granule cells toward the pia, and yet some cells still break away to migrate inward, it is proposed that when granule cells  
15 are ready to migrate, they may lose responsiveness to SDF-1.

Such a change in responsiveness could be mediated at least in part by B ephrins and EphB receptors, a model consistent with the observed inhibitory effect of EphB2-Fc on SDF-1 responsiveness of granule cells, as well as the up-regulation of ephrin-B2 and EphB2 gene expression by granule cells around the time of migration onset in mouse  
20 cerebellum. Ephrin-B 1 and EphB2 were also reported to be expressed by migrating granule cells in chick cerebellum (Karam et al., 2000). Consistent with this model, explant culture experiments show that at the time of migration onset, cerebellar granule cells lose their responsiveness to a chemoattractant in the pia. When granule cells start to travel inwards, they presumably still need to be responsive to other signals, allowing  
25 them to migrate and find their destination in the internal granule cell layer. BDNF could

promote this inward migration, since it is a chemoattractant for cerebellar granule cells, as shown here, and since the inward migration is impaired by BDNF gene knockout. The selectivity observed for EphB2 in inhibiting responsiveness to SDF-1 but not BDNF suggests a developmental model where ephrin signaling could act as a switch, changing  
5 the balance of preference from SDF-1 to other guidance cues. Such a model, while consistent with the presently known data, is in no way intended to limit other possible models that may also be consistent.

Finally, it is interesting to consider why regulation in this context might be mediated by ephrins, providing a bi-directional signaling system requiring direct cell-cell  
10 contact. One possibility could be autocrine signaling by granule cells. An alternative model is suggested by the observation that developing granule cells do not migrate independently, but rather in contact with other granule cells and radial glial fibers (Rakic, 1990; Hatten, 1999). Persistence of SDF-1 expression may ensure that granule cells do not migrate in isolation. Cell-cell contact could then activate ephrin signaling, and allow  
15 migration once granule cells are assembled with the correct cellular partners. Other models are also possible.

Contact-mediated cell-cell signaling can allow spatial precision, and bi-directional control. Forward signaling through Eph receptors is well established to precisely guide cell and axon migration. Genetic and embryological studies have shown B ephrin  
20 reverse signaling can affect processes involving migration or morphogenesis, and the presently claimed inventions shows that soluble EphB-Fc receptor can directly regulate cell guidance. Ephrin signaling can thus allow contact-mediated bi-directional regulation of guidance. This may allow coordinated movement within a cell population, or mutual regulation of interacting cell populations.

Our results also provide a mechanism for a receptor not in the seven-transmembrane class to regulate G protein signaling. In addition to the effect seen herein on cerebellar cells, it is proposed that ephrin reverse signaling affects leukocyte chemotaxis to chemokines, thereby providing a means for treatment of inflammation and other diseases. More generally, it is proposed that regulation through PDZ-RGS proteins provides a pathway to control many processes regulated by G proteins.

The presently claimed invention provides a means for selective regulation of responsiveness to guidance factors. Throughout the nervous system, the immune system, and elsewhere, such mechanisms are likely to have critical roles in allowing migrating cells and axons to appropriately modulate their responses, as they leave their point of origin, pass intermediate guideposts, and arrive at their final targets.

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What is claimed is:

1. An amino acid sequence having a PDZ domain and an RGS domain.
2. A protein comprising an amino acid sequence substantially identical to that shown in SEQ ID NO: 1.
- 5 3. A nucleic acid encoding the amino acid sequence according to claim 2.
4. A nucleic acid that hybridizes to the nucleic acid according to claim 3.
5. A recombinant vector comprising the nucleic acid according to claim 3.
6. A recombinant cell containing the vector according to claim 5.
7. A protein according to claim 2, wherein the protein is encoded by a gene from a  
10 vertebrate.
- 8 A protein according to claim 7, wherein the vertebrate is a mammal.
9. A protein encoded by a gene, the protein having an RGS domain and a PDZ domain, the PDZ domain being capable of binding to a portion of a cytoplasmic domain of an ephrin-B2 in a cell.
- 15 10. A protein according to claim 9, wherein the binding occurs in a two-hybrid system in a yeast cell, wherein the ephrin-B2 cytoplasmic domain is used as the bait of the system.
11. A protein according to any of claim 9, wherein the mammalian cDNA library is obtained from a tissue selected from the group consisting of an embryo, a tumor or a  
20 leukemia.
12. A protein according to claim 11, wherein the tumor is of neural origin.
13. A protein according to claim 12, wherein the tumor of neural origin is a neuroblastoma.

14. A protein according to claim 2, wherein the protein causes stimulation of ephrin-B1 induced de-adhesion of embryonic test cells at levels of ephrin-B1 that are suboptimal for dissociation.
15. A protein according to claim 14, wherein the stimulation is at least 2-fold.
- 5 16. A protein according to claim 15, wherein the stimulation is at least 4-fold.
17. A protein according to claim 16, wherein the stimulation is at least 8-fold.
18. A protein according to claim 14, wherein the stimulation is dependent on the presence of an amino acid sequence present in the carboxy terminal RGS domain.
19. A protein according to claim 14, wherein the stimulation is reversed in a dose-  
10 dependent manner in the presence of the amino terminal PDZ domain and in the absence of the carboxy terminal RGS domain.
20. A protein according to claim 15, wherein the embryonic test cells are from an embryo of a cold-blooded vertebrate.
21. A protein according to claim 20, wherein the vertebrate is an amphibian.
- 15 22. A soluble ephB2 receptor capable of binding a cell, such that a pattern of migration of the cell is altered.
23. A method of altering sensitivity of a cell to a chemokine, comprising:  
transmitting a reverse signal from a recombinant soluble ephB2 receptor to  
20 a transmembrane protein in the cell which is a ligand of the ephB2 receptor;  
binding a cytoplasmic protein, the cytoplasmic protein having an RGS domain and a PDZ domain, to the cytoplasmic domain of the transmembrane protein in the cell; and

altering a reaction of a G-protein coupled receptor (GPCR) in the membrane of the cell, such that the cell has altered sensitivity to a chemoattractant chemokine.

24. A method according to claim 23, wherein the cell is a granule cell located in an external granule cell layer (EGL) of a developing brain cerebellum.
25. A method according to claim 23, wherein the cell is involved in a process selected from the group consisting of cell migration, blood vessel formation, axon pathway selection, and rhombomere compartmentation.
26. A method according to claim 23, wherein the transmembrane protein is substantially homologous to an ephrin-B2.
27. A method according to claim 23, wherein the chemokine is an SDF-1.
28. A method according to claim 23, wherein transmission of the reverse signal requires a presence of the PDZ-RGS3 protein in the cell.
29. A method according to claim 27, wherein transmission of the reverse signal causes loss of responsiveness of the cell to the SDF-1 chemokine.
30. A method according to claim 23, wherein the cell is a leukocyte.
31. A method according to claim 30, wherein the method by which the cell has altered sensitivity to the chemokine is a treatment for an inflammatory condition or an autoimmune disease.
32. A method according to claim 23, further comprising omitting the recombinant soluble ephB2, and screening for a chemical agent that substitutes functionally for the omitted ephB2.
33. A method according to claim 23, further comprising adding a test sample to screen for an agent that alters sensitivity of the cell to the chemokine.

34. A method of modulating an intracellular pathway involved in cell migration upon the event of a cell to cell contact, comprising:

initiating ephrin signaling by providing cell to cell contact in a cell having a cytoplasmic protein, the cytoplasmic protein having an amino terminus that interacts with the carboxy terminus of ephrin, and having a carboxy terminus that affects a GTP-linked reaction of a seven transmembrane protein, causing the cell in the presence of sufficient chemokine to otherwise inhibit such migration from an initial anatomical location and towards a target location.

35. A method according to claim 34, further comprising selecting the cell from a granule cell and a leukocyte, such that the cytoplasmic protein mediates an intracellular pathway, or causing a granule cell to migrate away from the external granule cell layer (EGL), or causing the leukocyte to migrate into an inflamed tissue.

36. A method of screening in a test sample for the presence of an agent that alters *in vivo* functional interactions among the components of an ephrin-B signal pathway involving chemoattraction by a chemokine, comprising:

placing chemokine-sensitive cells having the ephrin-B ligand on a top side of a filter in an upper chamber of a transwell system, wherein the filter has pores of uniform size and separates the upper chamber from a lower chamber, and wherein the lower chamber contains the chemokine;

adding a test sample to the lower chamber; and

analyzing the lower side of the filter to determine an amount of migration of the cells into the lower chamber.

37. A method according to claim 36, having a second transwell such that adding a test sample to the lower chamber of the second transwell is omitted as a control, and further

comparing the amount of migration of cells in the presence and absence of the test sample is an indication of the effect of the agent on cell migration.

38. A method according to claim 36, wherein the cells are selected from a purified preparation of cerebellar granule cells and a pure cultured leukocyte cell line.
- 5 39. A method according to claim 38, wherein the chemokine is SDF-1.
40. A method according to claim 36, wherein the lower chamber contains the chemokine at a sub-optimal level.
41. A method according to claim 40, wherein the agent causes a decrease in cell migration in comparison to the second transwell control.
- 10 42. A method according to claim 41, wherein the agent is an anti-inflammatory or an anti-autoimmune therapeutic composition.
43. A method according to claim 40, wherein the agent causes a increase in cell migration in comparison to the control.
44. A method according to claim 43, wherein the agent is a novel chemokine.
- 15 45. A method according to claim any one of claims 41 or 43, wherein the agent is a low molecular weight synthetic organic chemical.
46. A pharmaceutical composition for delivering to a selected site an effective dose of a protein having an RGS domain and a PDZ domain capable of altering the sensitivity of a cell to a chemokine comprising an effective dose of said protein and a suitable carrier, and optionally additional active or inert ingredients such as
- 20 diluents, stabilizers, and excipients.
47. A pharmaceutical composition according to claim 46, further comprising a substance which allows for the slow release of the pharmaceutical composition at the selected site.

48. A pharmaceutical composition according to claim 46, wherein the selected site for delivery is a tumor site.
49. A pharmaceutical composition according to claim 46, wherein the selected site for delivery is an allergic response site.
- 5 50. A pharmaceutical composition according to claim 46, wherein the selected site for delivery is an autoimmune response site.
51. A pharmaceutical composition for delivering to a selected site an effective dose of a soluble protein having an Eph receptor ectodomain, said soluble protein being capable of altering a cell signaling pathway comprising:
- 10           an effective dose of said soluble protein;
- a suitable carrier; and optionally
- additional active or inert ingredients such as diluents, stabilizers, and excipients.
52. A pharmaceutical composition according to claim 51, wherein the soluble protein is a fusion protein.
- 15 53. A pharmaceutical composition according to claim 52, wherein the soluble fusion protein comprises GST and the C-terminal 33 amino acids of ephrin B receptors.
54. A pharmaceutical composition according to claim 51, further comprising a substance which allows for the slow release of the pharmaceutical composition at the selected site.
- 20 55. A pharmaceutical composition according to claim 51, wherein the selected site for delivery is a tumor site.
56. A pharmaceutical composition according to claim 51, wherein the selected site for delivery is an allergic response site.
57. A pharmaceutical composition according to claim 51, wherein the selected site for delivery is an autoimmune response site.
- 25



58. A viral vector comprising the nucleic acid sequence encoding the protein of claim 2.
59. A plasmid comprising the nucleic acid sequence encoding the protein of claim 2.
60. A plasmid vector encoding the protein of claim 52.
- 5 61. A plasmid vector encoding the protein of claim 53.

02535/00001 197161.1

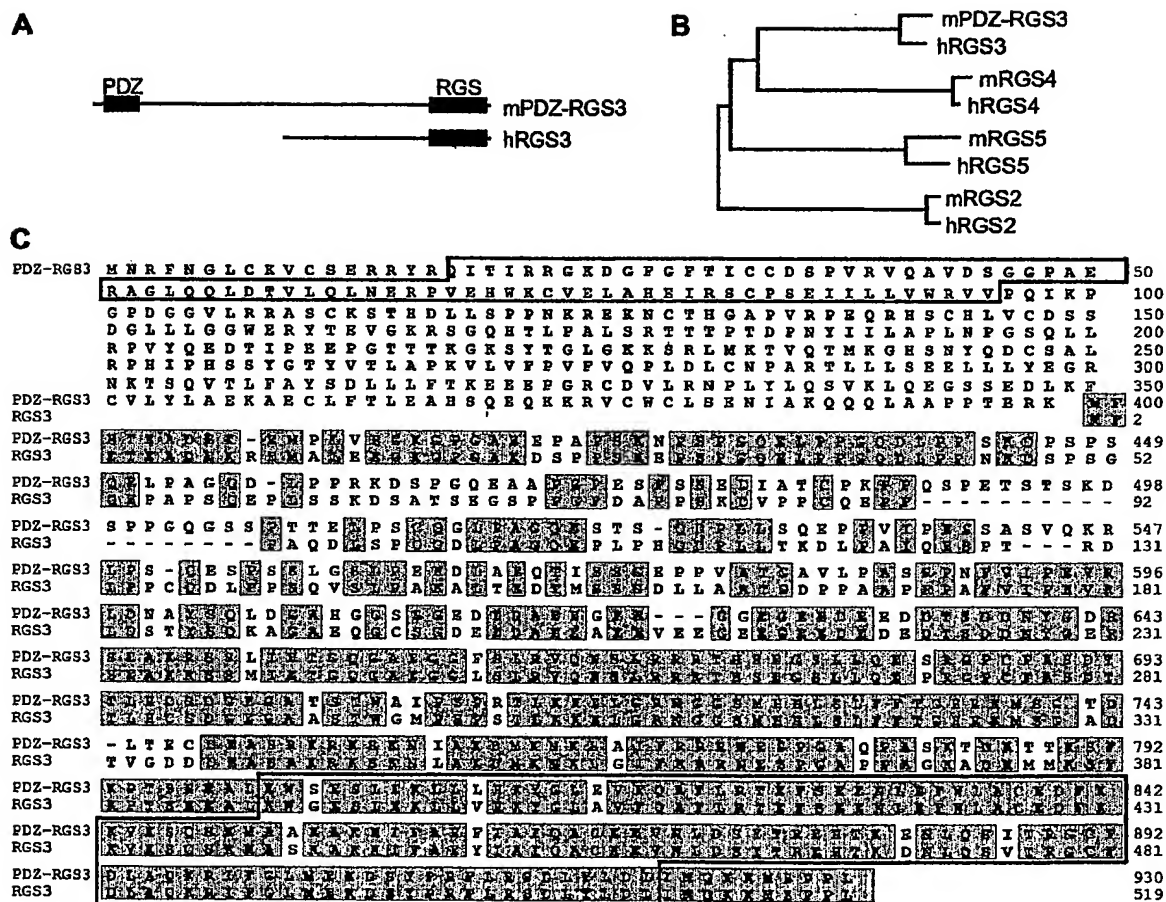


FIGURE 1

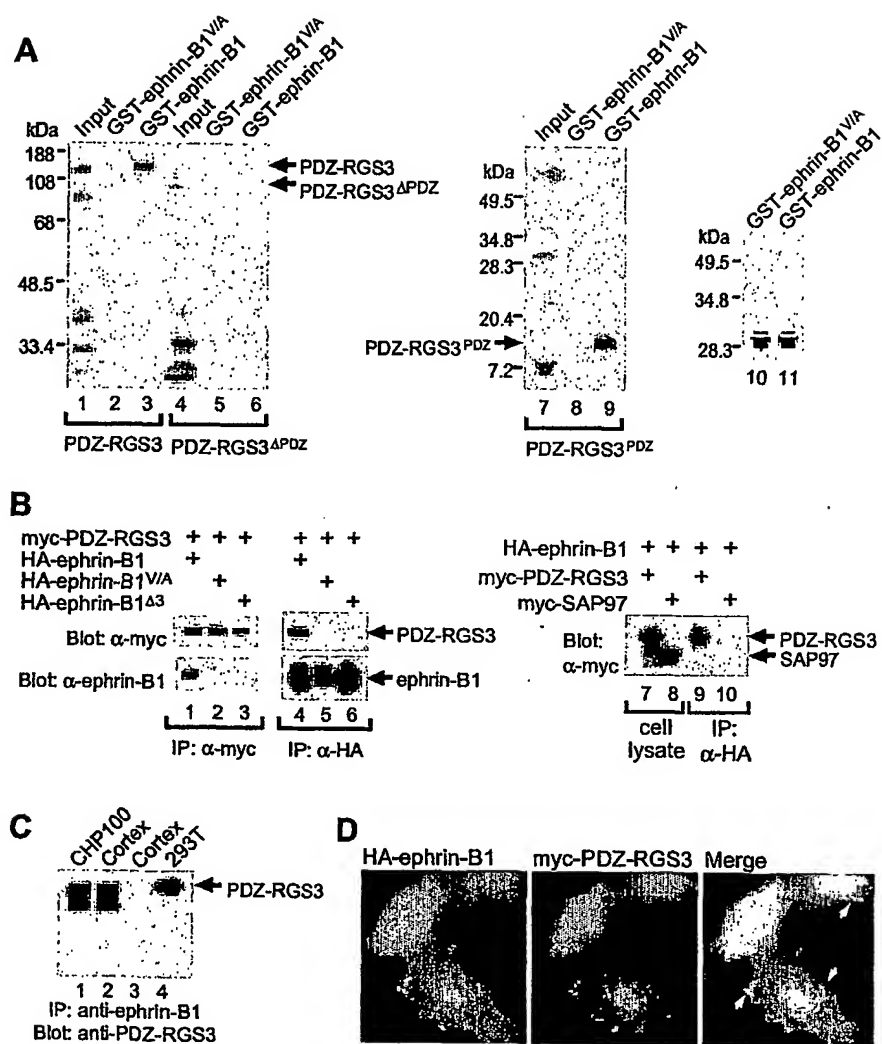


FIGURE 2

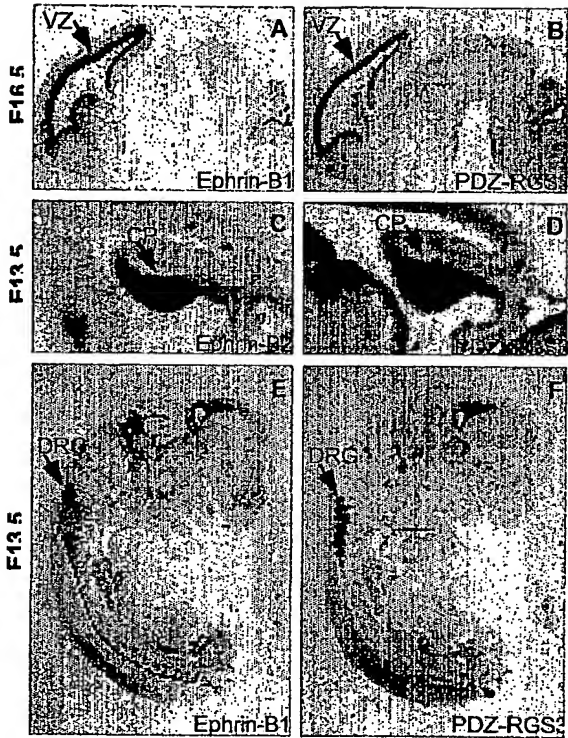


FIGURE 3

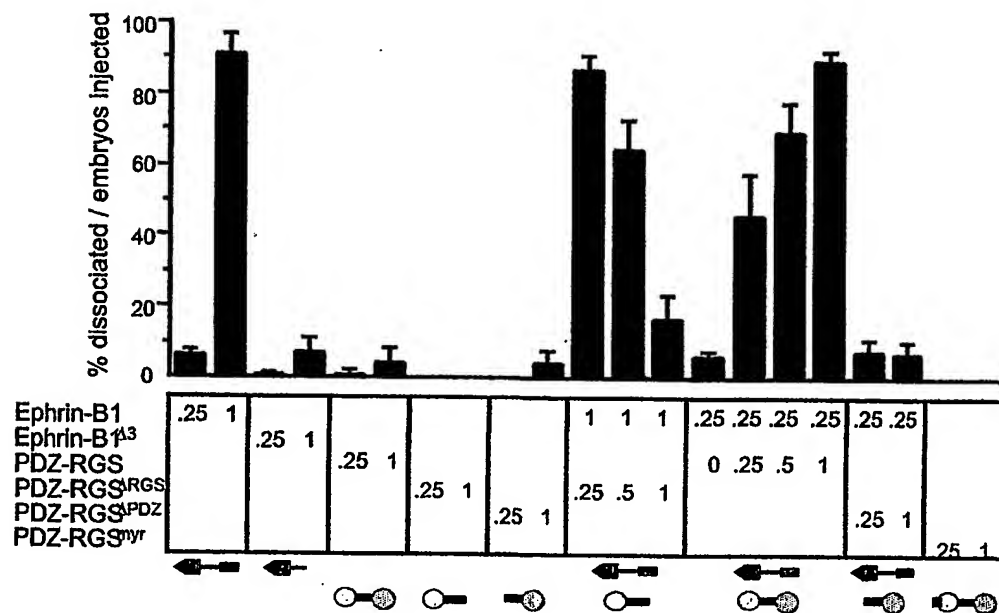


FIGURE 4

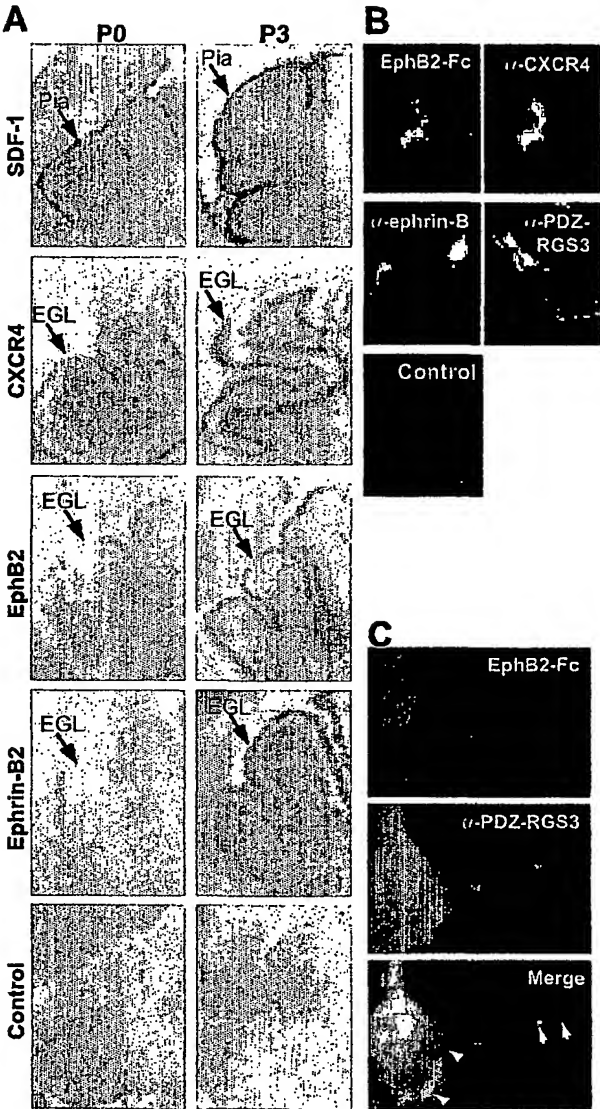


FIGURE 5

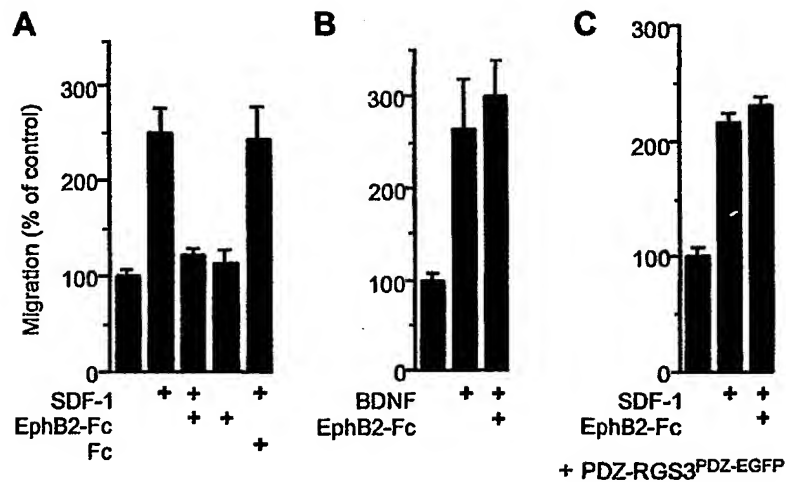
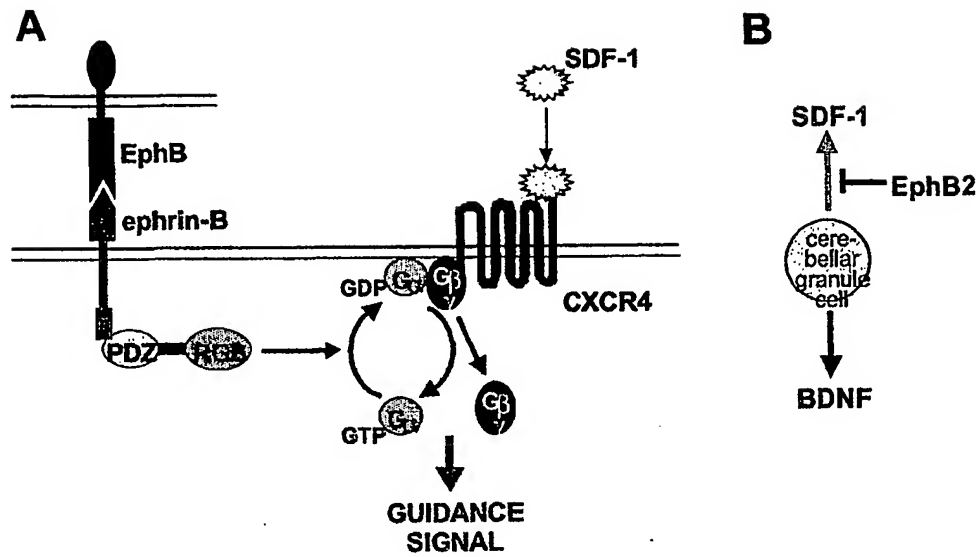


FIGURE 6





## SEQUENCE LISTING

&lt;110&gt; Flanagan et al.

<120> B EPHRIN REGULATION OF G-PROTEIN COUPLED  
CHEMOATTRACTION

&lt;130&gt; 2535/102

&lt;140&gt; Not Assigned

&lt;141&gt; 2001-03-30

&lt;160&gt; 2

&lt;170&gt; FastSEQ for Windows Version 4.0

&lt;210&gt; 1

&lt;211&gt; 930

&lt;212&gt; PRT

&lt;213&gt; Mus musculus

&lt;400&gt; 1

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## SEQUENCE LISTING

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&lt;120&gt; B-Ephrin Regulation

&lt;130&gt; 2535/001

&lt;160&gt; 4

&lt;170&gt; FastSEQ for Windows Version 4.0

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